Searches for FCNC tqγ Couplings*

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*study is based on arXiv:1701.06932 and arXiv:1705.05419

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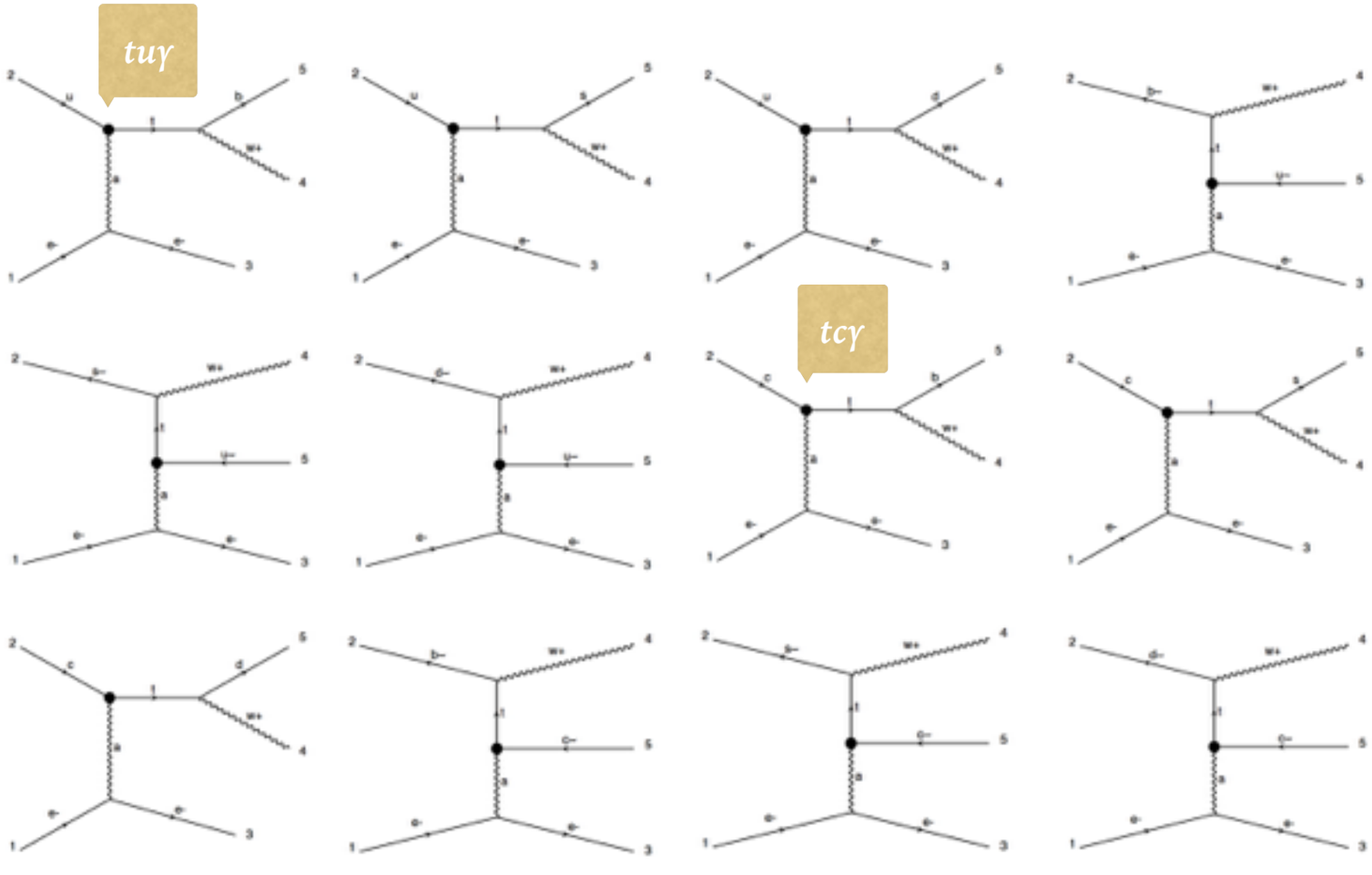
The top quark FCNC (tqγ) interactions are described by an effective Lagrangian

$$L_{eff} = \frac{g_e}{2m_t}\bar{t}\sigma^{\mu\nu}(\lambda_u^L P_L + \lambda_u^R P_R)uA_{\mu\nu} + \frac{g_e}{2m_t}\bar{t}\sigma^{\mu\nu}(\lambda_c^L P_L + \lambda_c^R P_R)cA_{\mu\nu} + h.c.$$

LH coupling | RH coupling | LH coupling | RH coupling

In this study, no specific chirality is assumed for FCNC tqγ, then we take $\lambda_q^L=\lambda_q^R=\lambda_q$. Production process is $e^-p\to e^-Wq+X$.

There are also similar diagrams for process $e^-p\to e^-W^-q+X$ with the interchange $q\leftrightarrow q\sim$.

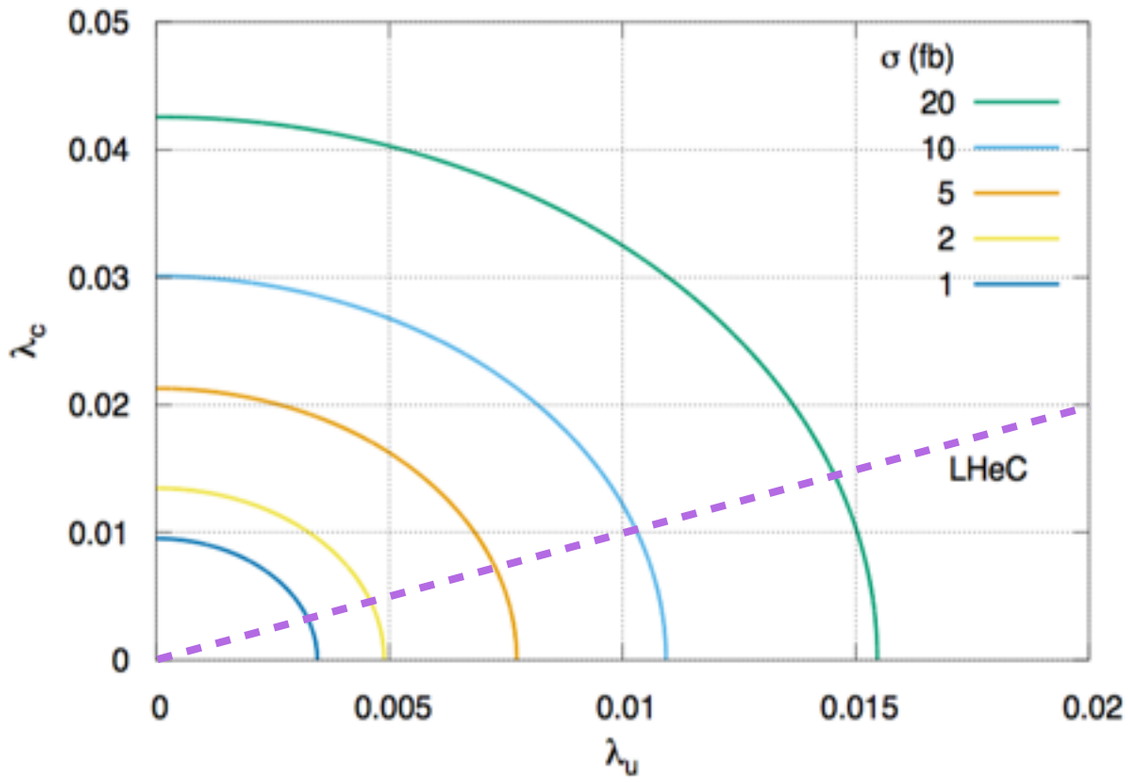


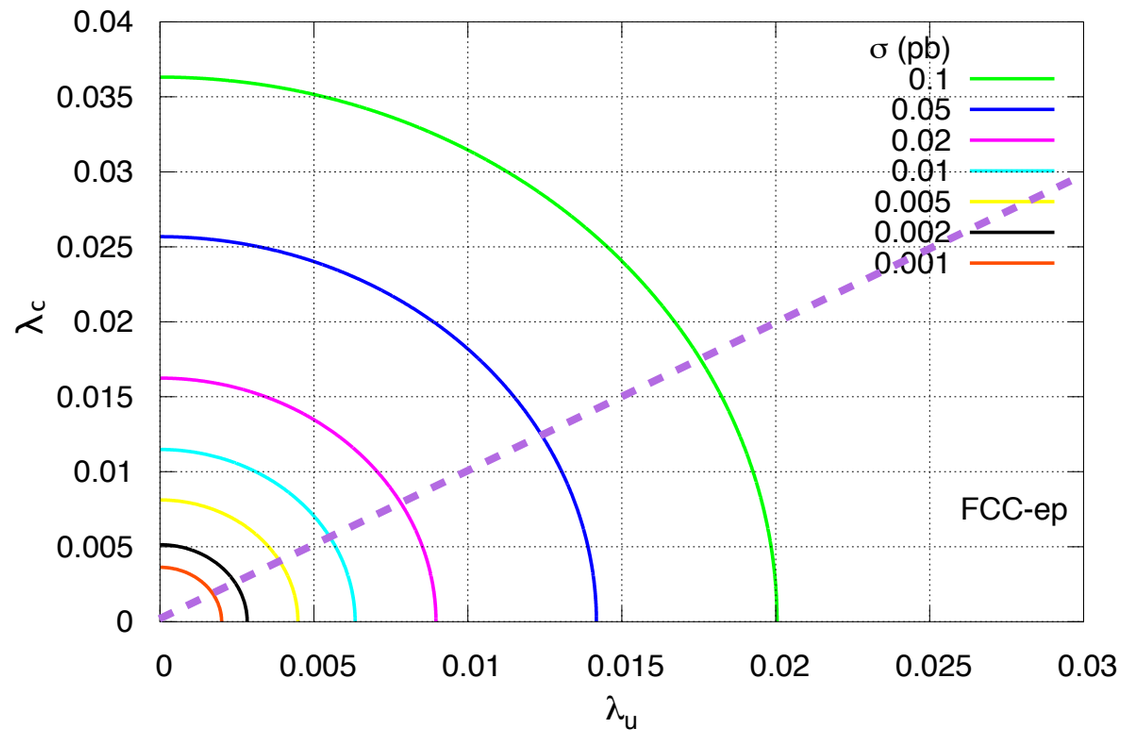
Process: $e^-p \to e^-Wq+X$

A contour plot for top FCNC tqγ couplings λ_u and λ_c within the interested range depending on different signal cross sections at LHeC collider.

A similar plot depending on the cross section values at FCC-eh. The dashed line corresponds to equal coupling values ($\lambda_u = \lambda_c$) and the sensitivity to λ_c are more pronounced at FCC-eh.

In order to reach a target value of λ_u=0.01, corresponding signal cross section values can be predicted as 8 fb at LHeC and 25 fb at FCC-eh.

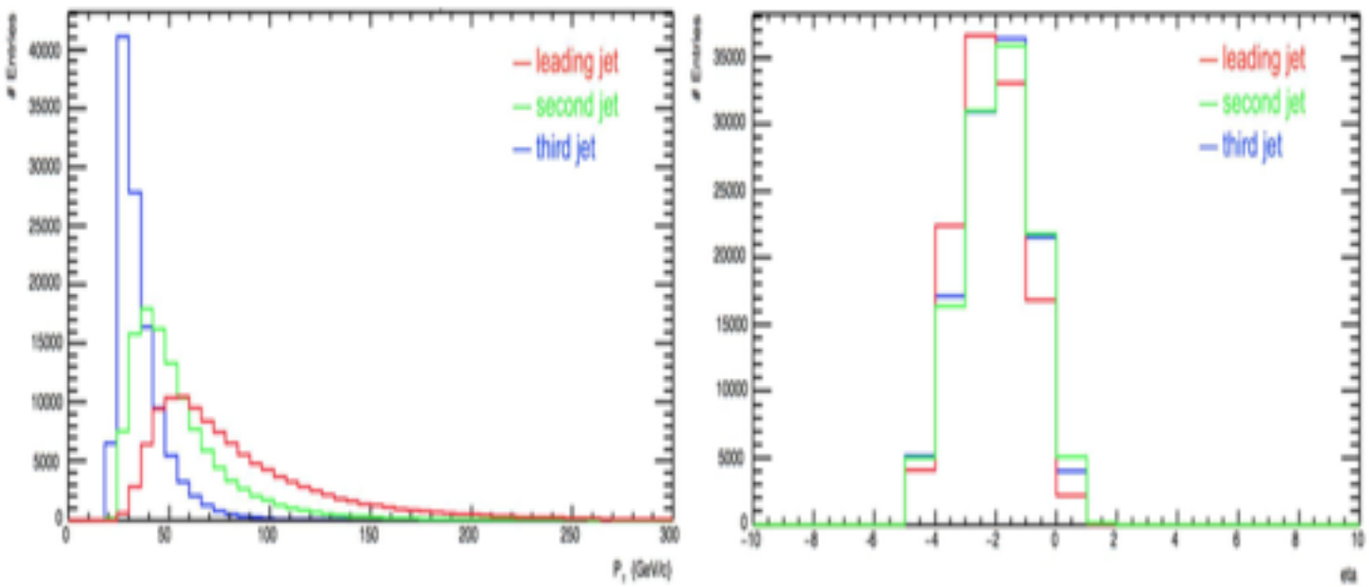




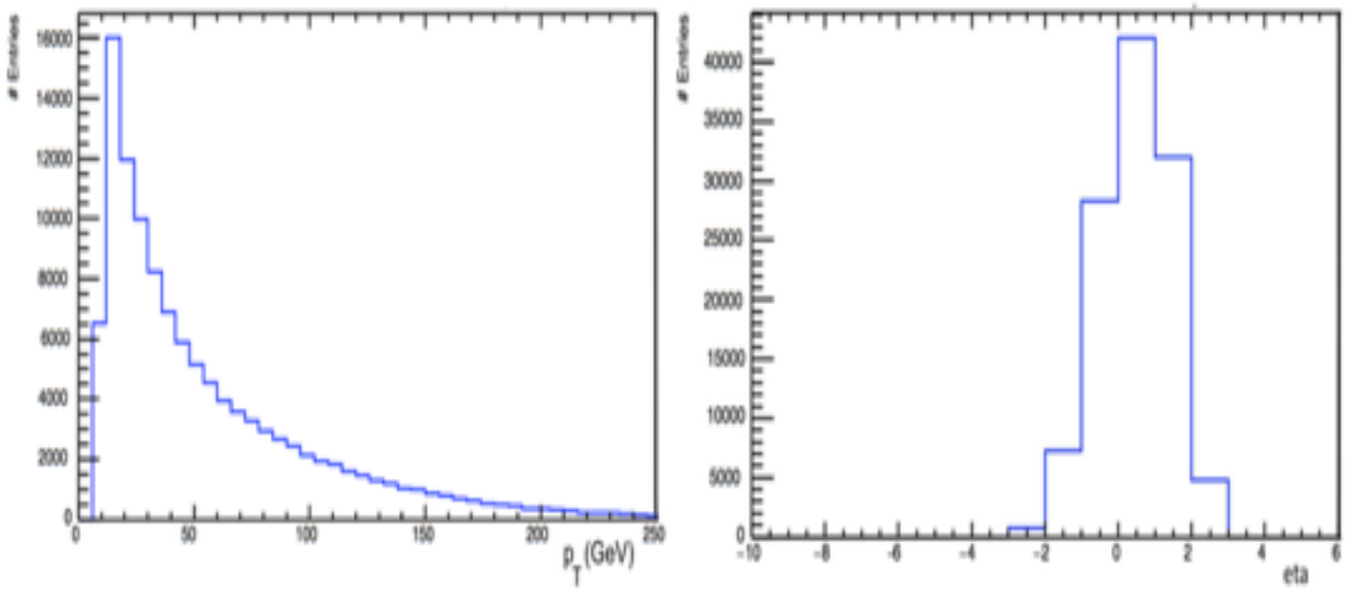
Kinematical distributions

LHeC

Transverse momentum and pseudo-rapidity distributions of three jets from the process $e^- p \to e^- W^\pm q + X$ which includes both the interfering background and signal for $\lambda_u=\lambda_c=0.05$ at the LHeC.

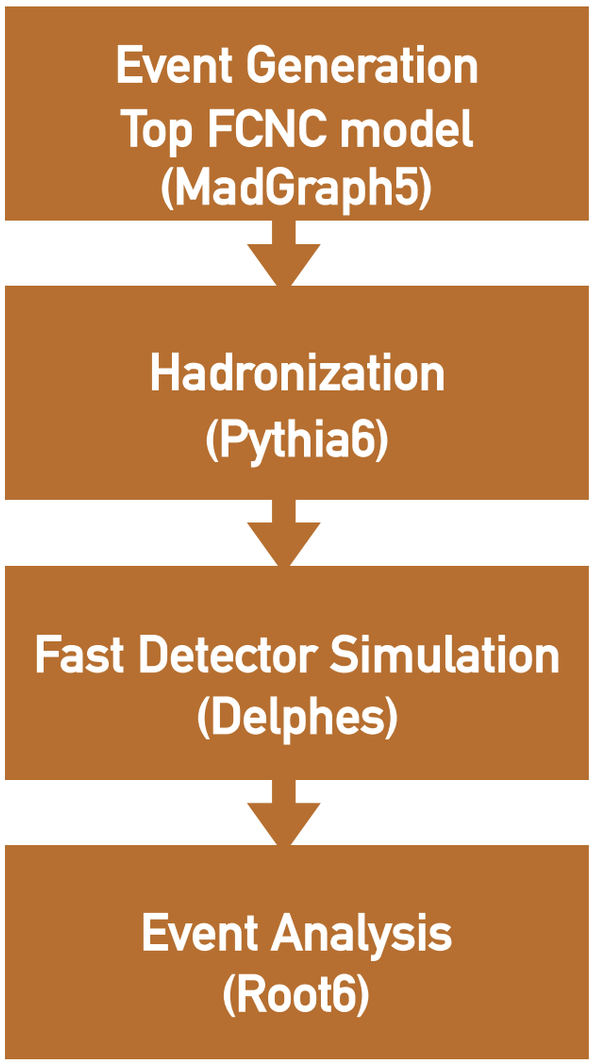


Transverse momentum and pseudo-rapidity distribution of electron for the process $e^- p \to e^- W^\pm q + X$ which includes $S+B_W$.



Analysis

For the analysis, after pre-selection cuts, we use the analysis cuts for further background suppression.



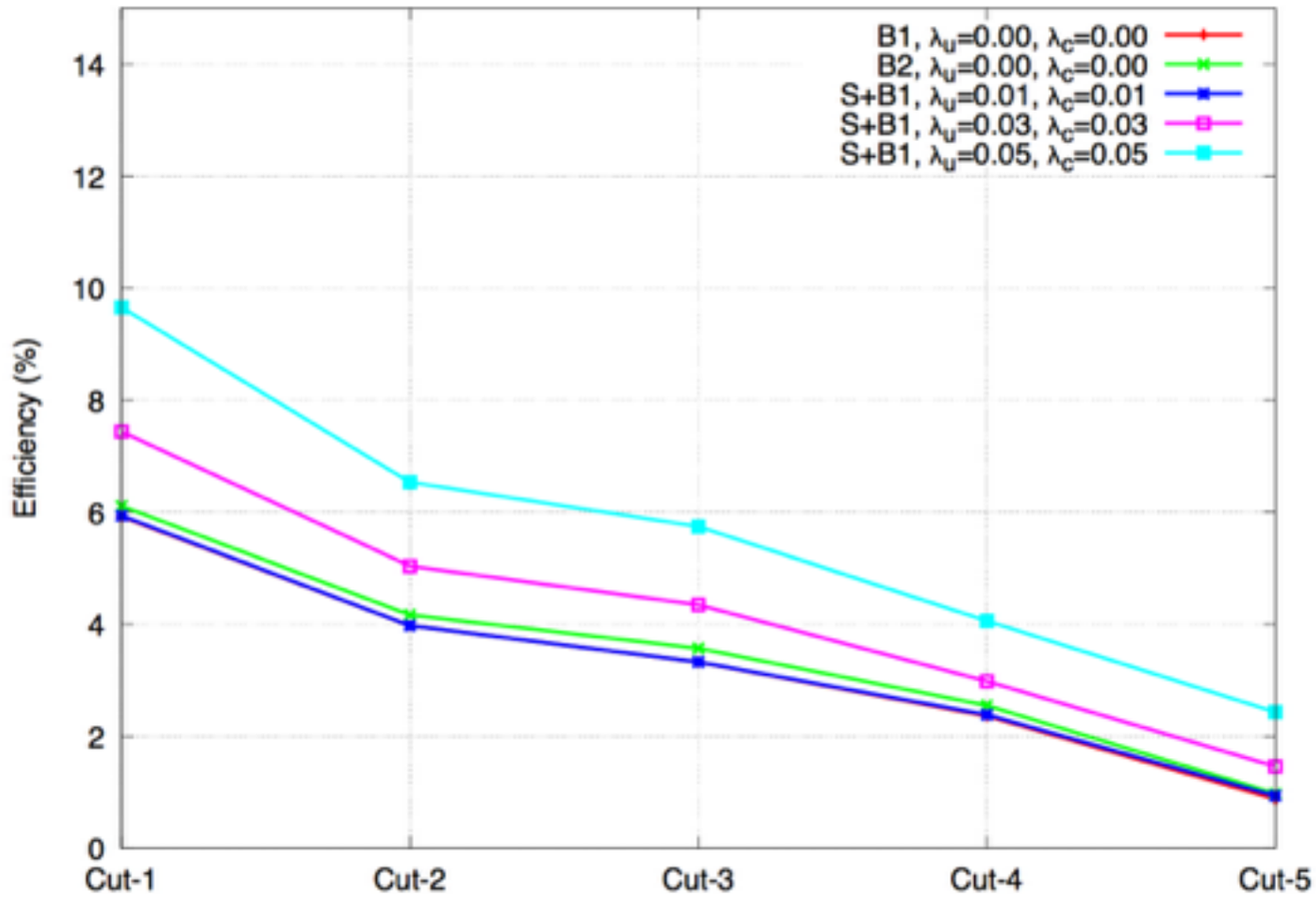
cut flow

Cut-0 :	**at least one electron and three jets (pre-selection with default MG5 cuts)**
Cut-1 :	require one of three jets as being b-tag
Cut-2 :	b-tagged jet has transverse momentum p_T>35 GeV and other jets have p_T>25 GeV, and electron has p_T>20 GeV
Cut-3 :	all jets have pseudo-rapidity -5.0<η<0 ; and electron has -2.5<η<2.5
Cut-4 :	invariant mass of two jets within 50<m_{jj}<90 GeV (for W- boson)
Cut-5 :	invariant mass of three jets (for top) between 130<m_{bjj}<200 GeV

LHeC

Cut efficiency

Efficiency plot for the cuts applied at each step for the analysis of signal (S) +background B1(eWq) and eZq(B2) events. The cut efficiencies are calculated with respect to the preselection cuts for each coupling value.



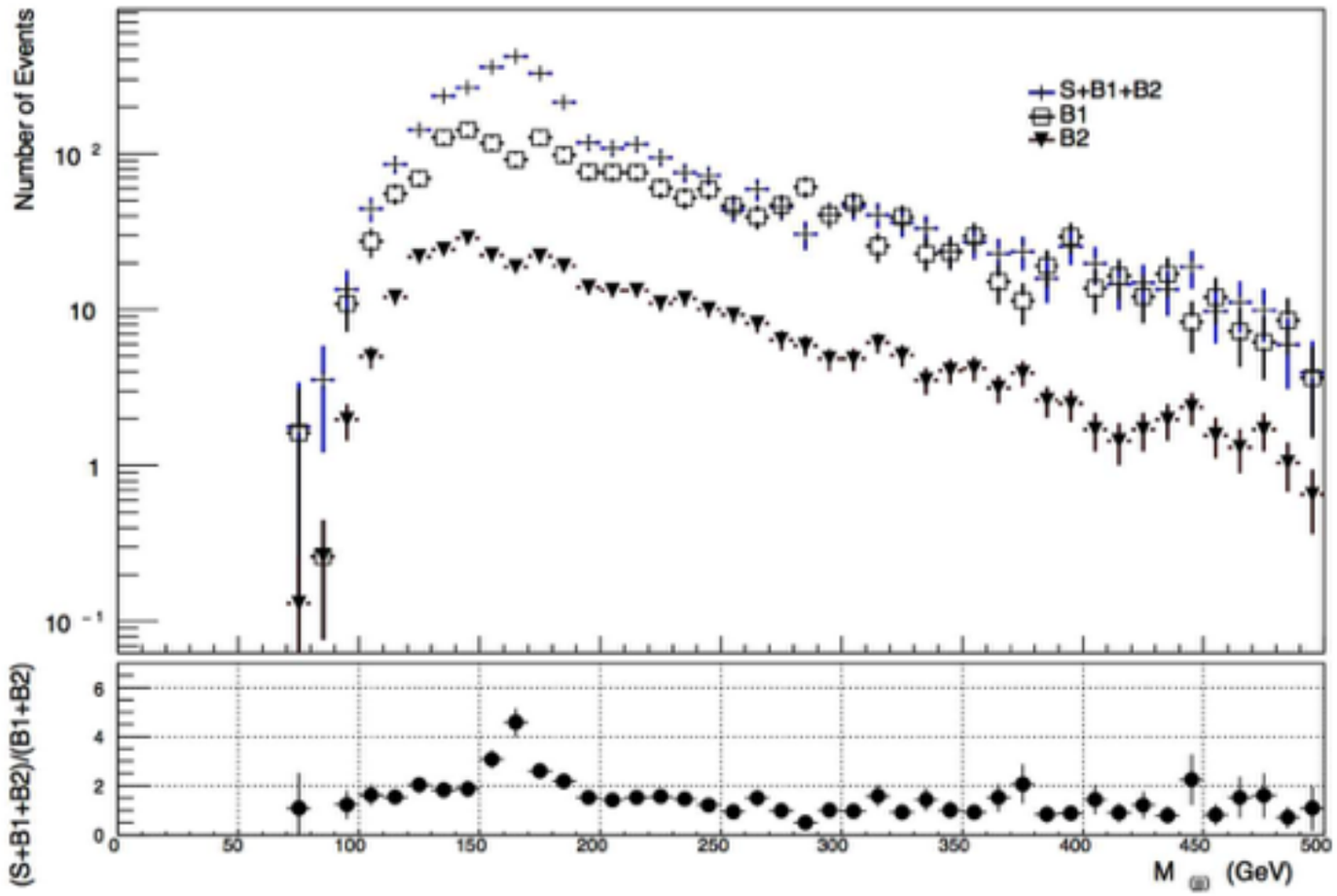
The number of events (N) for background B1 (B2), and signal for different values of λ_u and λ_c at LHeC with L_{int} = 100 fb^{-1}.

N	$\lambda_c = 0$	$\lambda_c = 0.01$	$\lambda_c = 0.03$	$\lambda_c = 0.05$
$\lambda_u = 0$	584 (149)	592	609	640
$\lambda_u = 0.01$	617	621	692	763
$\lambda_u = 0.03$	943	969	1003	1209
$\lambda_u = 0.05$	1502	1744	1758	1792

Invariant mass distributions

LHeC

Invariant mass distributions of three jets (one of the jets is required as b-jet) for the signal +background (S+B1+B2), and backgrounds (B1, B2). The ratio plot presents the signal (for equal coupling scenario λ=0.05) strength which peaks at the top mass.



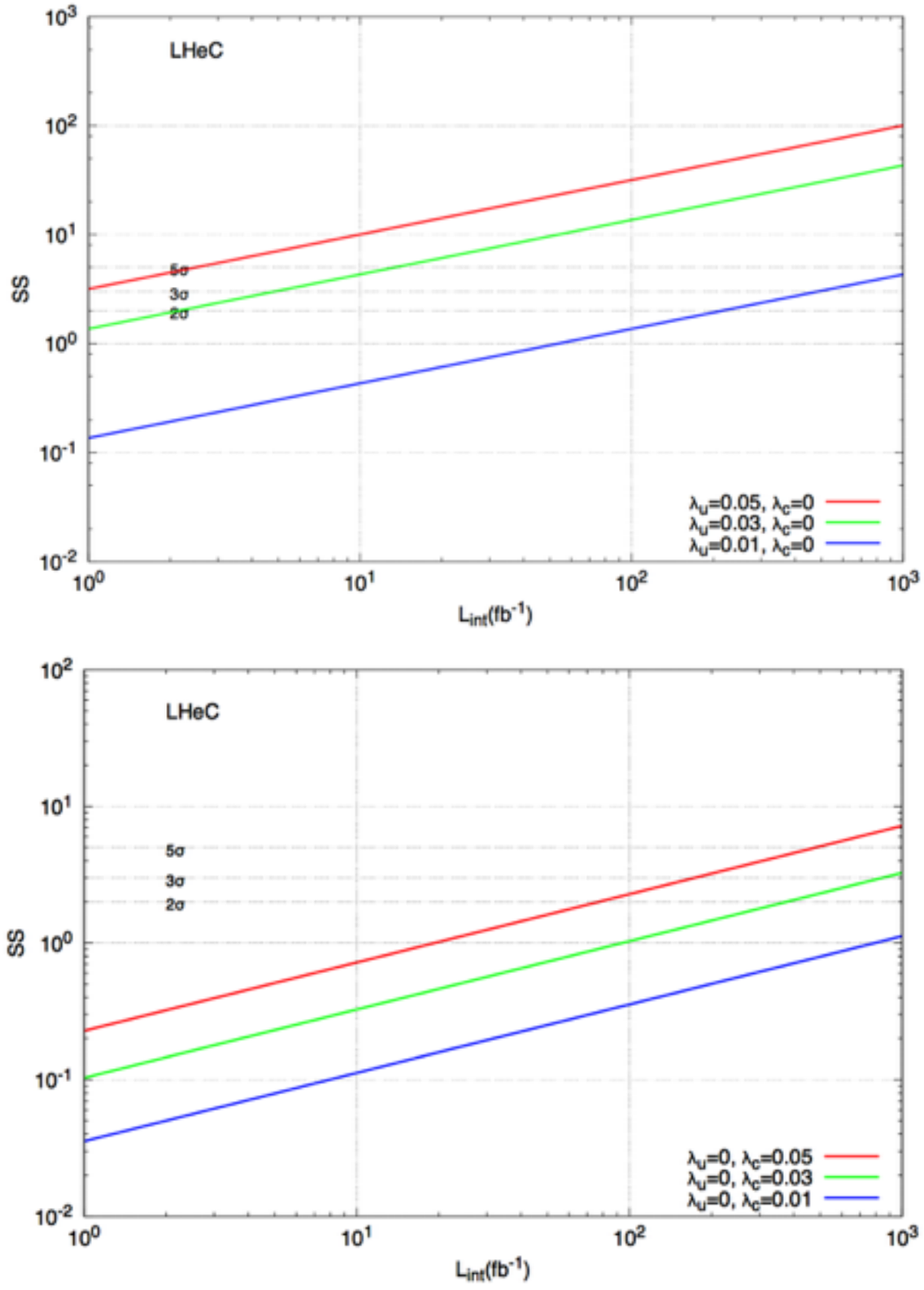
The statistical significance (SS) are calculated at the final stage of the cuts using the signal (S) and total background (B) events.

$$SS = \sqrt{2[(S+B)\ln(1+\frac{S}{B}) - S]}$$

Statistical significance

Estimated statistical significance (SS) reach of flavor changing neutral current **tuγ coupling** (λ_u) depending on the integrated luminosity ranging from 1 fb^{-1} to 1 ab^{-1} at the LHeC. It includes the contribution from the main backgrounds on the results. The signal significance corresponding to 2σ, 3σ and 5σ lines are also shown.

The SS reach for the flavor changing neutral current **tcγ coupling** (λ_c) depending on the integrated luminosity at the LHeC.



Analysis of the signal and background at FCC-eh

Studied processes: $e^-p \to e^-Wq+X$ and $e^-p \to e^-Wbq+X$

The event selection and cuts on kinematic variables are applied similarly. Our signal processes include on-shell W boson and it decays into two jets, therefore we classified the background according to e+V+jets which includes eWj (B_W) and eZj (B_Z), and we also consider the backgrounds eHj (B_H), $et\bar{t}$ (B_{tt}) and ebjj (B_{bjj}) backgrounds.

- The signal cross sections (pb) are shown in the following tables

$e^-p \to e^-Wb+X$

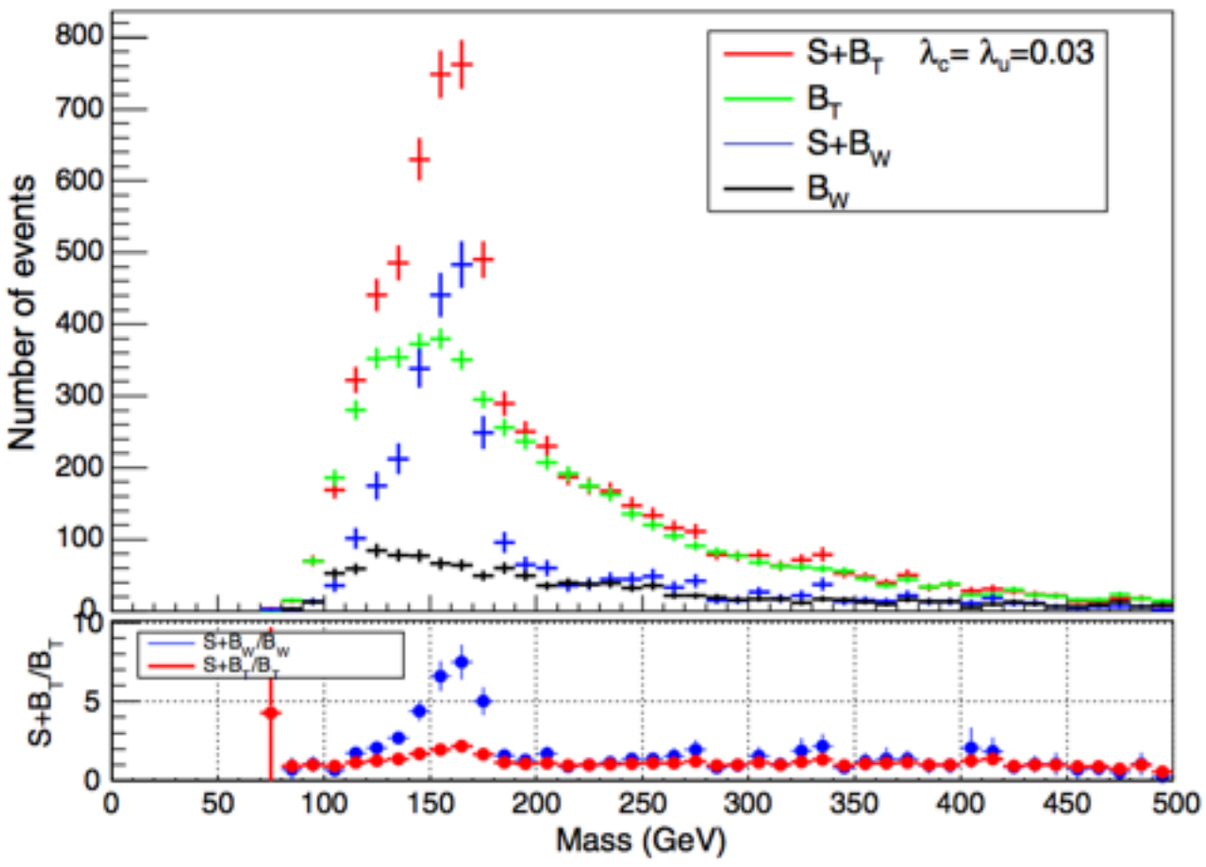
FCC-he	$\lambda_c = 10^{-2}$	$\lambda_c = 10^{-3}$	$\lambda_c = 0$
$\lambda_u = 10^{-2}$	3.238×10^{-2}	2.490×10^{-2}	2.488×10^{-2}
$\lambda_u = 10^{-3}$	7.834×10^{-3}	3.243×10^{-4}	2.480×10^{-4}
$\lambda_u = 0$	7.576×10^{-3}	7.580×10^{-5}	0

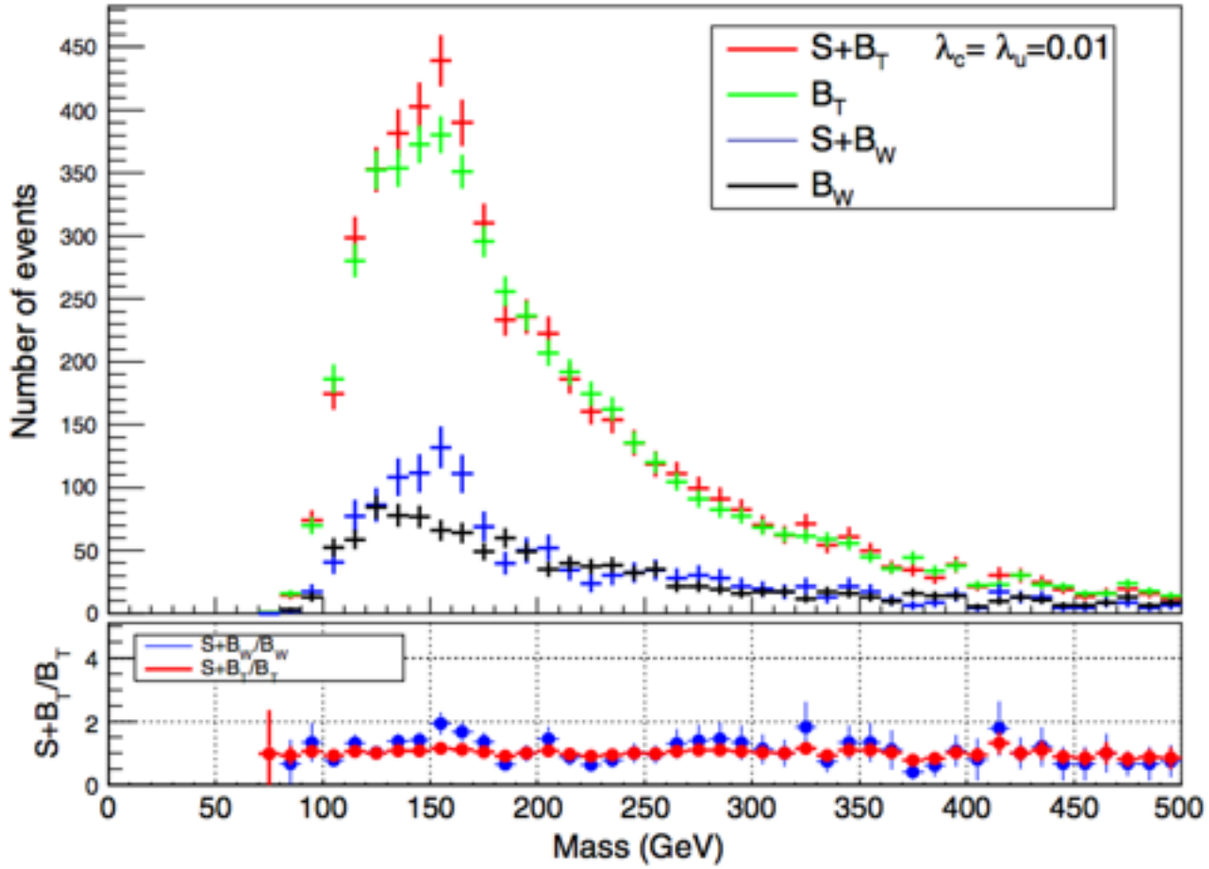
$e^-p \to e^-Wbq+X$

FCC-he	$\lambda_c = 10^{-2}$	$\lambda_c = 10^{-3}$	$\lambda_c = 0$
$\lambda_u = 10^{-2}$	8.106×10^{-3}	5.161×10^{-3}	5.150×10^{-3}
$\lambda_u = 10^{-3}$	3.032×10^{-3}	8.132×10^{-5}	5.142×10^{-5}
$\lambda_u = 0$	2.957×10^{-3}	2.973×10^{-5}	0

Invariant mass distributions

FCC-eh





Distributions of reconstructed top quark mass plots for signal, and relevant backgrounds, with different anomalous FCNC couplings. The lower part of each plot shows the relative ratio of ($S+B_T$) and B_T. Here, S is for signal and B_T for total background.

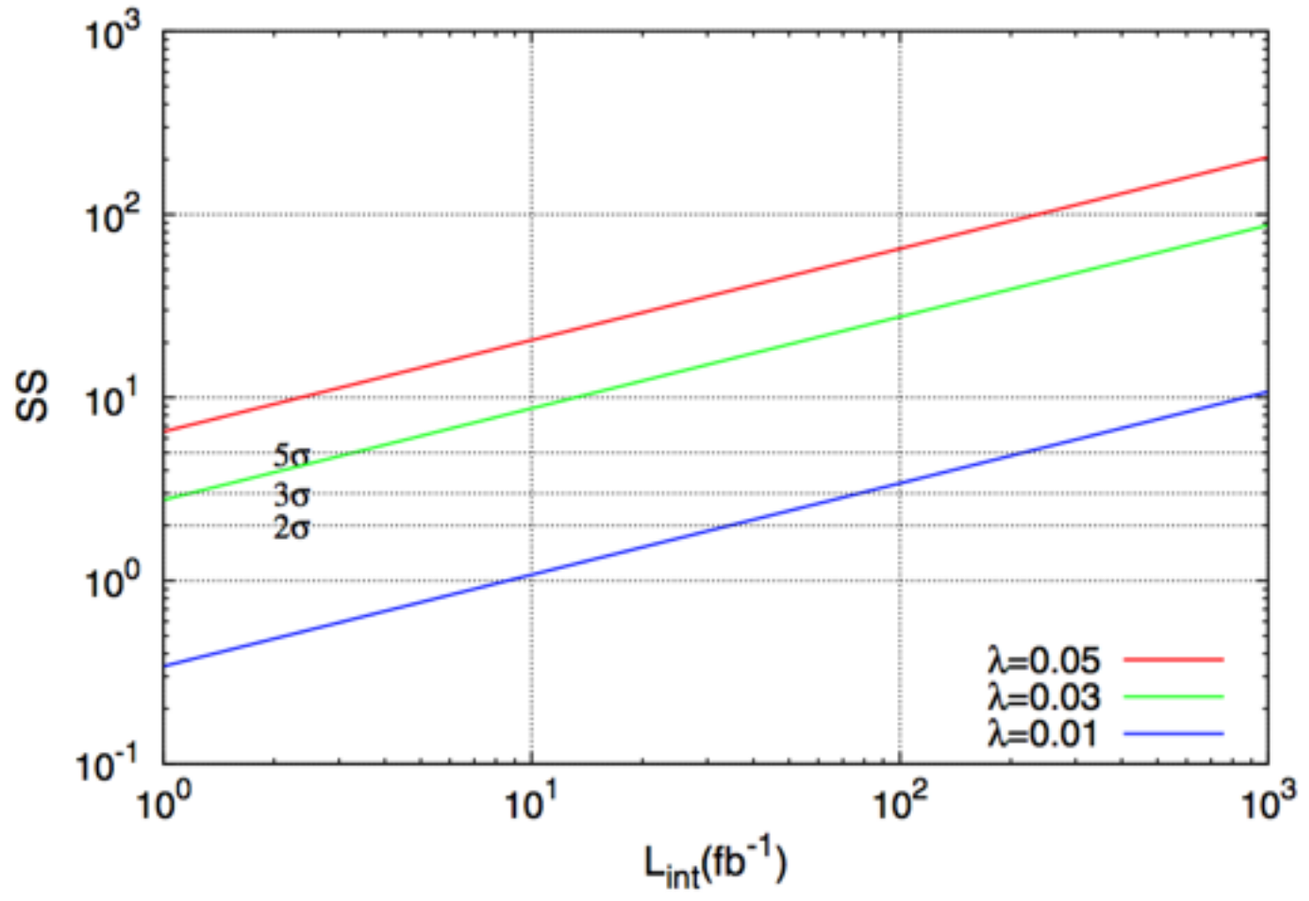
Number of events and statistical significance

FCC-eh

The number of signal (S) and relevant background events (B_W, B_H, B_Z, B_{tt}, B_{bjj}) after each kinematic cuts in the analysis with L_{int}=100 fb^{-1} at FCC-eh.

Processes	Cut-0	Cut-1	Cut-2	Cut-3	Cut-4	Cut-5
$S + B_W$ ($\lambda = 0.03$)	206373	11687	8665	7964	2867	1883
$S + B_W$ ($\lambda = 0.01$)	200135	7827	5776	5312	1396	622
S ($\lambda = 0.03$)	6695	4276	3218	2974	1683	1440
S ($\lambda = 0.01$)	457	416	329	322	212	179
B_W	199678	7411	5447	4990	1184	443
B_H	2279	979	802	757	107	47
B_Z	13420	1639	1145	956	246	110
B_{tt}	9752	5594	5339	4974	1079	460
B_{bjj}	48241	17287	9936	9074	2573	1170

On the right (bottom) plot, the statistical significance (SS) depending on integrated luminosity for different anomalous FCNC couplings (λ) are shown for FCC-eh. The 2σ, 3σ and 5σ lines are also shown.



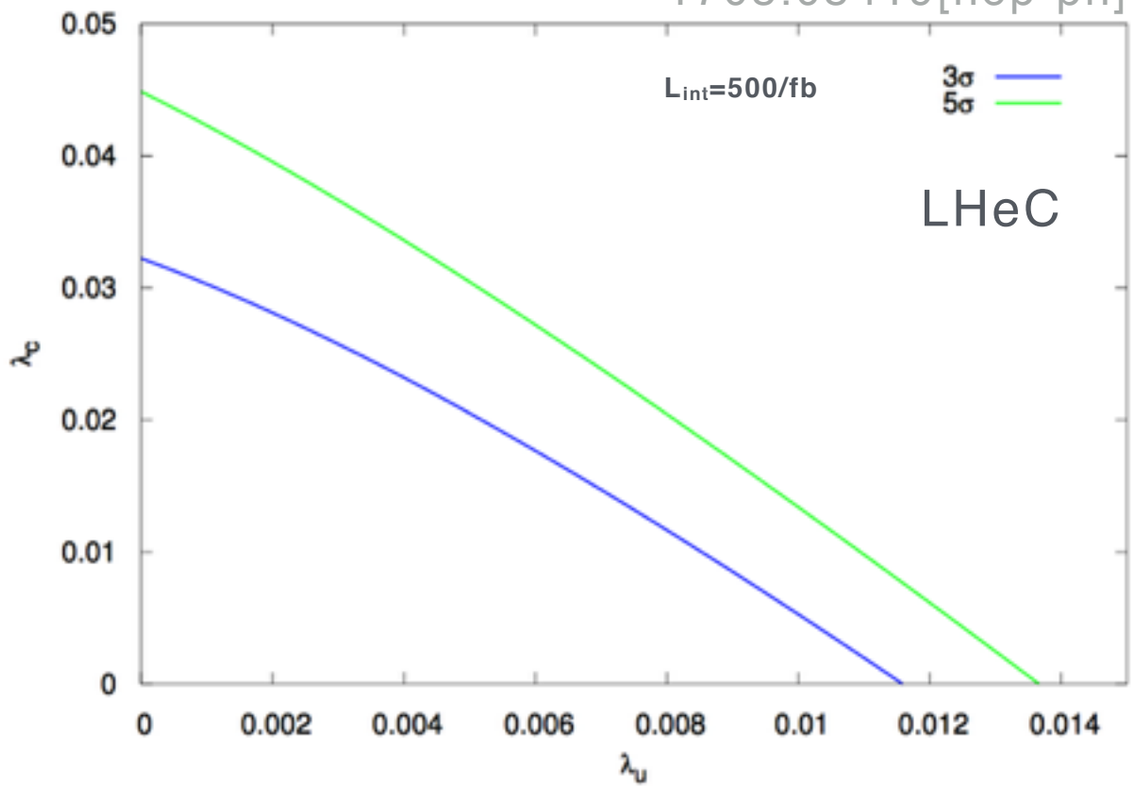
Results on couplings

The contour plot for the couplings λ_u and λ_c at LHeC for an integrated luminosity of 500 fb^{-1}. The 3σ significance results: λ_u= 0.012 and λ_c =0.032. The upper bounds on branching ratios: $BR(t\to u\gamma)<1.62\times10^{-5}$ and $BR(t\to c\gamma)<1.15\times10^{-4}$ at LHeC.

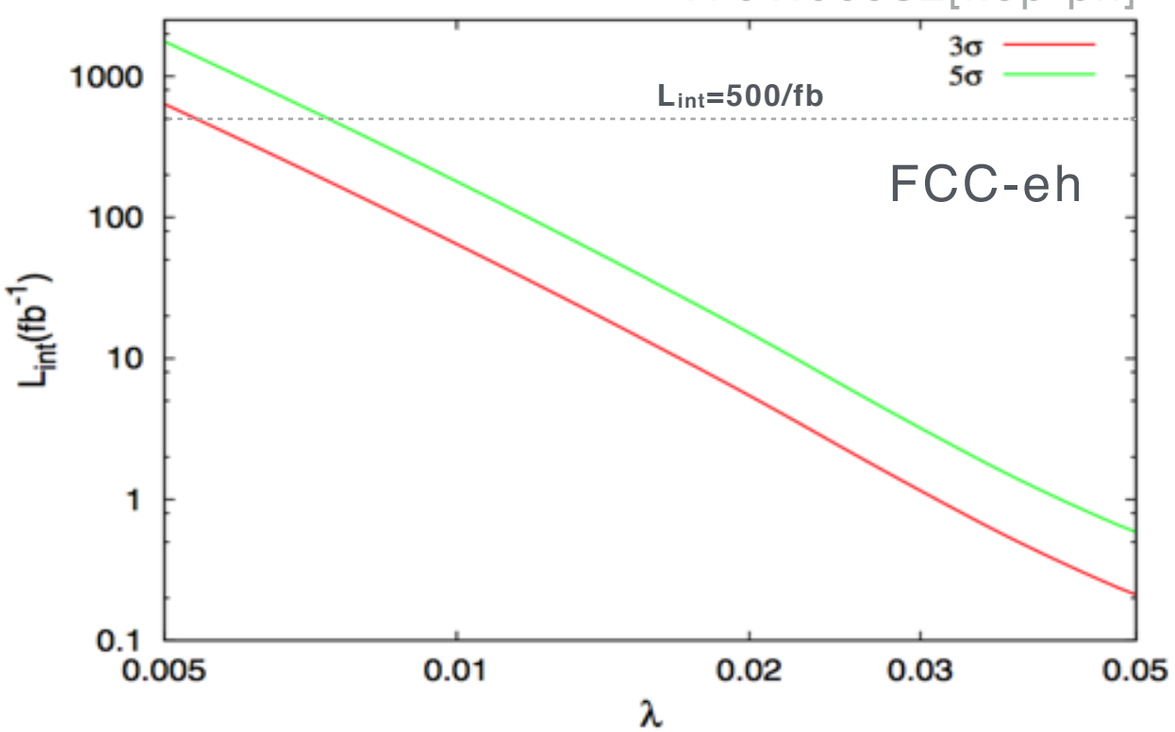
On the right (bottom) plot, the integrated luminosity versus anomalous FCNC coupling (λ) at 3σ and 5σ significance is shown for FCC-eh. The results can be compared to the HL-LHC expected limits*.

* The expected limits on tqγ couplings at HL-LHC have already reported in Ref.[ATLAS Collaboration, arXiv: 1307.7292], the branching ratios for $t\to q\gamma$ are 8×10^{-5} and 2.5×10^{-5} for L_{int} = 300 fb^{-1} and 3000 fb^{-1}, respectively.

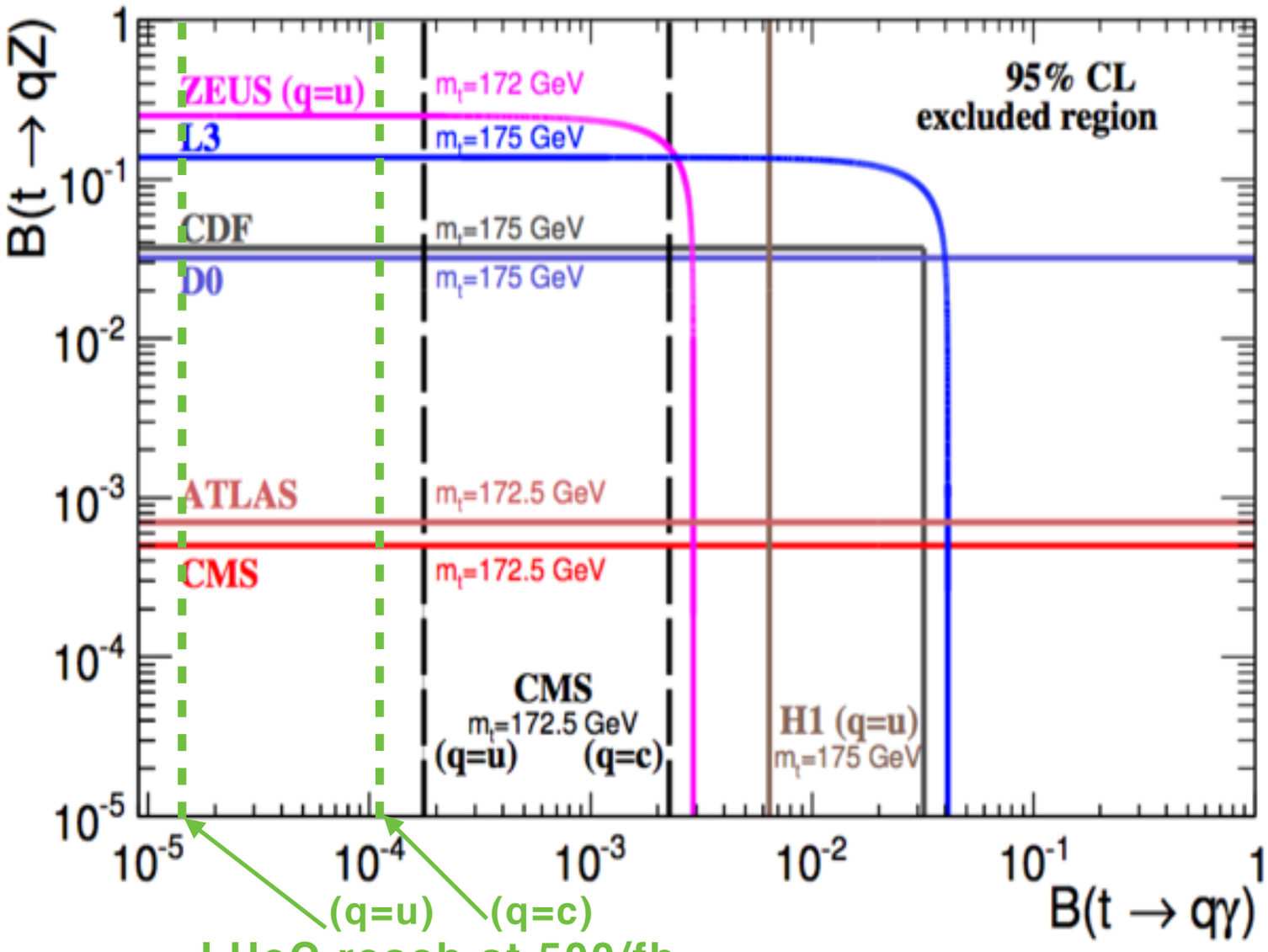
1705.05419[hep-ph]



1701.06932[hep-ph]



Current experimental limits on tqγ and tqZ



The measured upper limits on B(t→qZ) versus B(t→qγ) from different experiments. The two vertical dashed lines show recent results (L_{int}=19.8/fb) of the analysis of CMS experiment [CMS Collaboration, JHEP04 (2016) 035].

Conclusion

At the LHeC, we have analyzed the process $e^-p \to e^-W^{\pm}q+X$ with the signature including one isolated electron and one b-jet together with two jets in the final state. The signal for this process includes the top quark flavor changing neutral current couplings (tqγ) through photon exchanges in electron-proton collisions. We obtain attainable upper limits on the top quark FCNC couplings from the analysis of signal and background including detector effects through the fast simulation.

The FCC-eh, with an electron energy of 60 GeV and a proton energy of 50 TeV, would provide significant single top quark production event rates via investigated channel. Top quark FCNC couplings ($\lambda>0.01$) can be searched at the level of significance greater than 3σ with an integrated luminosity of larger than 75 fb^{-1} at the projected FCC-he. The b-tagging has an important role in our study.

The future ep colliders LHeC and FCC-ep with the high luminosity of 1 ab^{-1} has the potential in probing the top FCNC couplings (λ_u, λ_c), which can be comparable or even better when compared to the bounds from the HL-LHC.

Thank you for attention!

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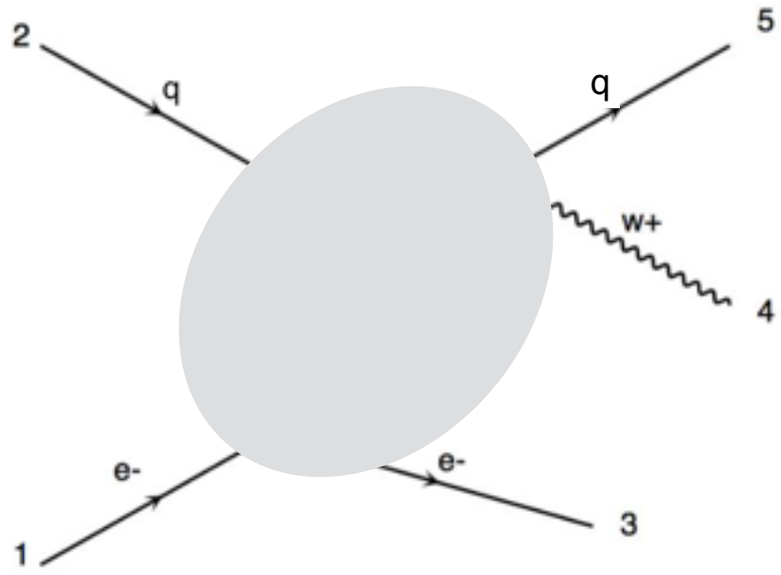
Current and expected limits on tqγ couplings

	LHC (CMS Obs. Limit at 19.8/fb)*	HL-LHC (Expec. Limit at 500/fb)**	LHeC (500/fb)***	FCC-eh (500/fb)***
B(t—>uγ)	1.3×10^{-4}	4.5×10^{-5}	1.6×10^{-5}	6.8×10^{-6}
B(t—>cγ)	1.7×10^{-3}	3.0×10^{-4}	1.1×10^{-4}	2.4×10^{-5}

* Current experimental limit on tqγ, 1511.03951[hep-ex].
** Expected limits for HL-LHC, CMS DP-2016-064.
*** Current study.

Cross section

Process: $e^-p \to e^-Wq+X$



Cross section (pb) for $S+B_W$ at LHeC

λ_u or $\lambda_c \to$	0.05	0.03	0.02	0.01	0
$\lambda_c = 0$	2.493	2.368	2.329	2.307	2.298
$\lambda_u = 0$	2.324	2.308	2.303	2.299	2.298
$\lambda_u = \lambda_c$	2.519	2.378	2.333	2.307	2.298

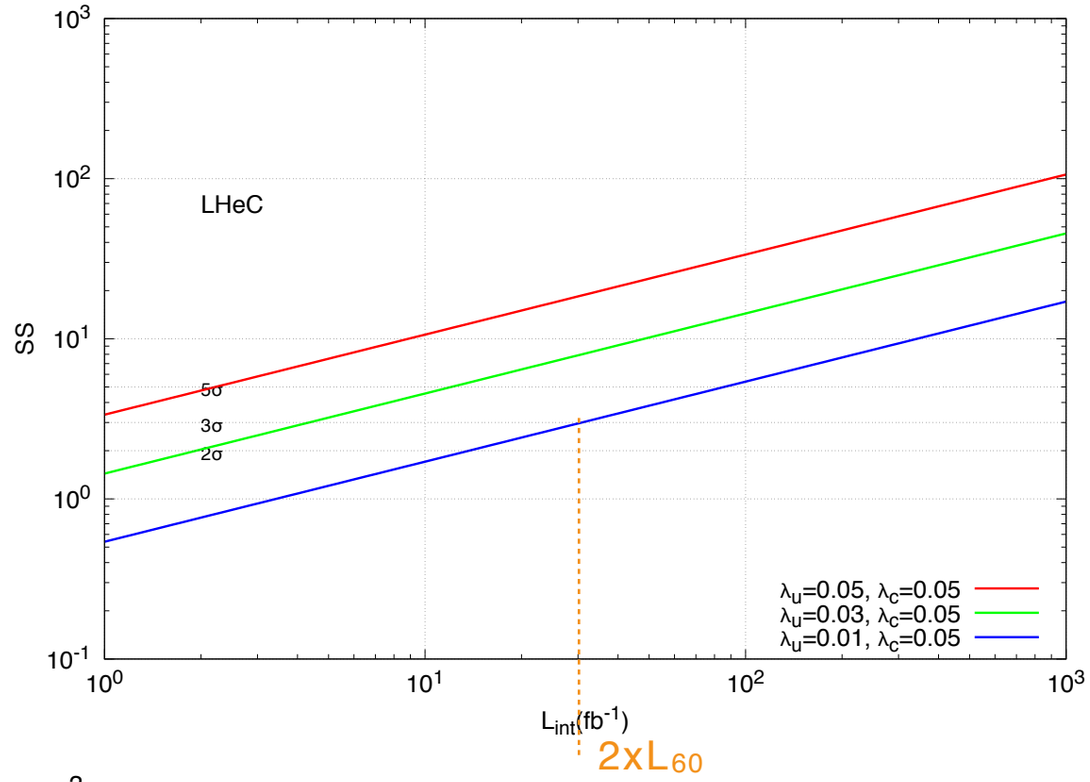
Cross section (pb) for $S+B_W$ at FCC-eh

λ_u or λ_c —>	10^{-1}	10^{-2}	10^{-3}
λ(tuγ)	10.72	8.58	8.57
λ(tcγ)	9.24	8.54	8.53
λ(tuγ,tcγ)	11.51	8.64	8.61

Comments on lower energy (electron beam) run

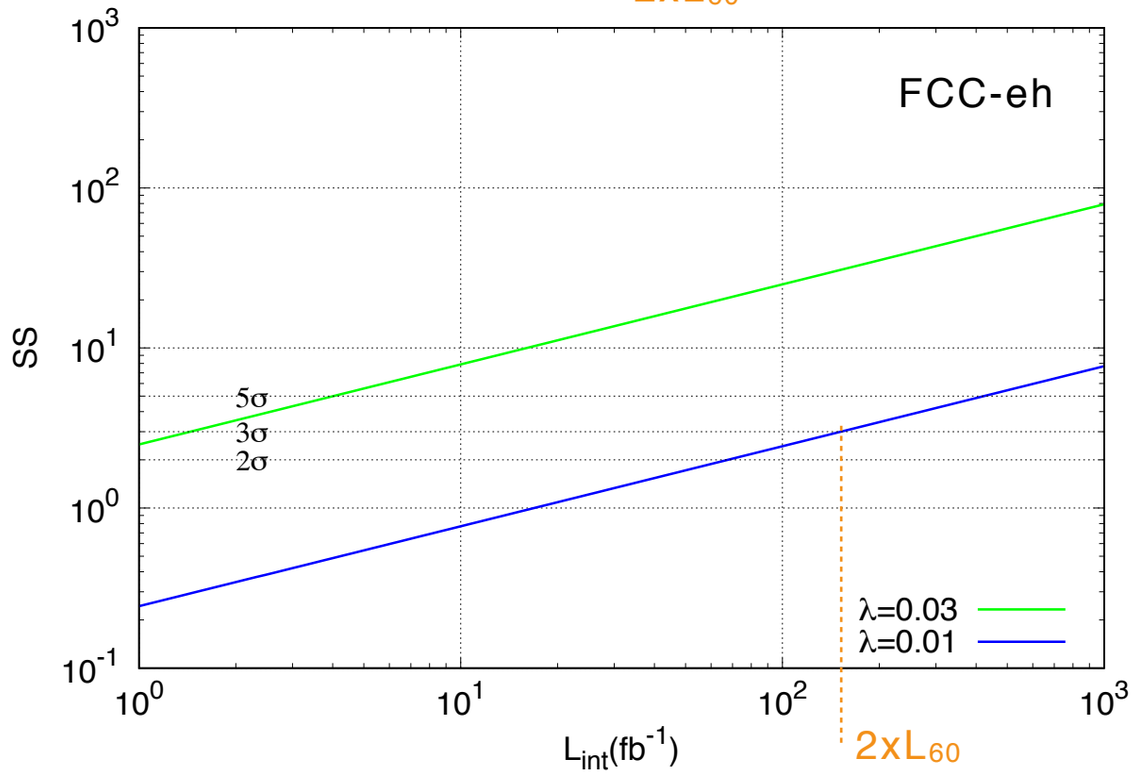
- An option with E_e=40 GeV and E_p=7 TeV

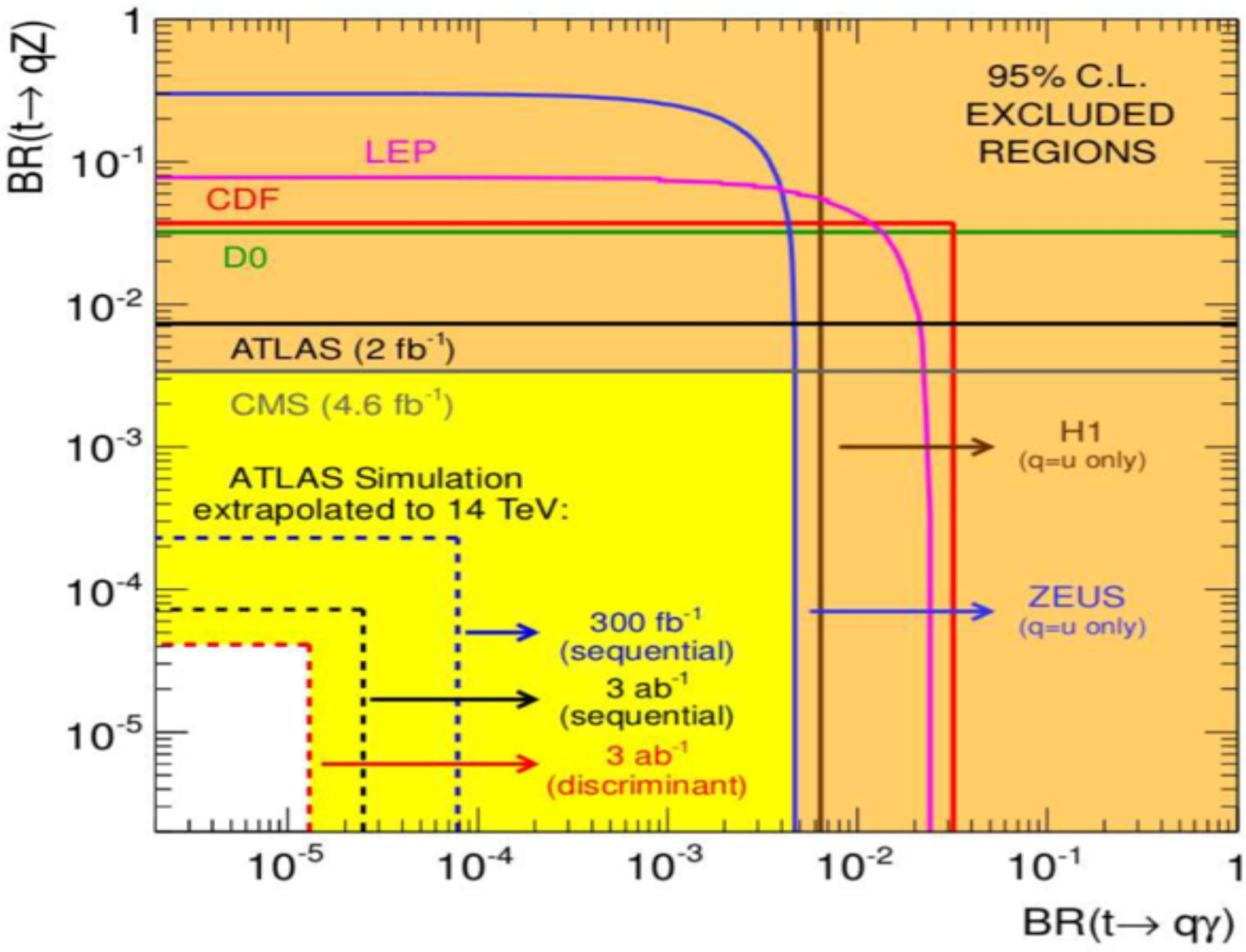
LHeC	Cross section (pb)	
λ	Ee=40 GeV	Ee=60 GeV
0.05	1.699	2.519
0.03	1.597	2.378
0.01	1.546	2.307



- An option with E_e=40 GeV and E_p=50 TeV

FCC-eh	Cross section (pb)	
λ	Ee=40 GeV	Ee=60 GeV
0.1	8.449	11.510
0.03	6.451	8.932
0.01	6.240	8.641





The present 95% CL. observed limits on the *BR*(*t*—>*q*γ) vs. *BR*(*t*—>*qZ*) plane are shown as full lines for the LEP, ZEUS, H1, D0, CDF, ATLAS and CMS collaborations. The expected sensitivity at ATLAS is also represented by the dashed lines. For an integrated luminosity of L_{int} = 3000 fb^{-1} the limits range from 1.3x10^{-5} to 2.5x10^{-5} (4.1x10^{-5} to 7.2x10^{-5}) for the *t*->*q*γ (*t*->*qZ*) decay. Limits at L_{int} =300 fb^{-1} are also shown [ATLAS Collaboration, ATL-PHYS-PUB-2013-007].